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Technical Lesson 14

INDUCTANCE

We now come to the subject of INDUCTANCE. It will be of great advantage to you to study this phase of the instruction thoroughly striving to master the fundamentals of inductance and its effect in alternating current circuits. Inductance plays a very important part in such circuits and, as the frequency of the current increases, its effect thereupon becomes more and more pronounced until, in circuits handling currents of radio frequency, it becomes a factor of predominant importance.

INDUCTANCE is best defined as that property of an electrical circuit which stores up energy in the form of electro-magnetic lines of force. Its effect is to oppose any change of current in the circuit and this opposition to a change in current is termed INDUCTIVE REACTANCE.

The property of inductance simply denotes a particular arrangement of a conductor or circuit, that is, the shape of the circuit, the materials of which it is formed, and the magnetic permeability of the medium surrounding it.

A circuit may have various values of inductance, in fact, a circuit may have as many inductances as it is possible to change the shape or form of the circuit.

The unit of inductance is the Henry and a circuit is said to have an inductance of one Henry when a current which is changing at the rate of one ampere per second induces an electromotive force of one volt in the circuit. This unit was named after a noted American scientist, Joseph Henry, who discovered many important electro-magnetic facts.

The Henry is too large a unit for use in radio frequency circuits hence the millihenry which is one thousandth ($1/1000$) part of a Henry, is used and, with the very high frequencies, the microhenry, which is one millionth part of a Henry, is frequently employed. The Henry is used as a unit of inductance in the lower frequency circuits of radio receivers and transmitters, such as in the radio and power circuits.

In the study of inductance the terms magnetic flux, magnetic field, and magnetic lines of force will frequently appear. They all mean one and the same thing.

The magnetic lines of force which surround a current carrying conductor are invisible and intangible and are, therefore, non existing

lines. The word lines is merely used as a convenient way to express or represent the path and direction of this invisible magnetic force which surrounds a current carrying conductor.

When any change is made in an existing circuit so that an increase in the number of magnetic flux lines cutting the circuit is produced per ampere of current, the inductance of the circuit will be increased. A straight conductor will possess relatively small inductance and, if the same conductor is wound in the shape of a helix or coil the inductance will be increased due to the fact that a greater part of the conductor, since it is in helix form, will be cut by a greater proportion of all the flux developed. When iron is used as the core a still greater concentration of magnetic flux takes place because the iron provides a better magnetic path for the flux than air alone.

To determine the inductance of a coil used in low frequency work and in which no iron is used, i.e., having an "air" core, the following formula may be applied: Assuming the coil of Figure 5 has 100 turns, the average radius of the coil is 3 inches, and its length is 9 inches, then

$$L = \frac{T^2 \times R^2}{l} \times .0000001 \quad \text{where } L = \text{inductance}$$

T = number of turns
R = radius of coil
l = length of coil
.0000001 = a constant

$$L = \frac{T^2 \times R^2}{l} \times .0000001$$

$$L = \frac{100^2 \times 3^2}{9} \times .0000001$$

$$L = \frac{10000 \times 9}{9} \times .0000001$$

$$L = \frac{90000}{9} \times .0000001$$

$$L = 10000 \times .0000001 = 0.001000$$

$$L = .001 \text{ Henry (or 1 milli-Henry).}$$

Now remember this;- the experiment and the working out of this problem has to do with alternating current circuits of low frequency. The formula, however, is changed but slightly with higher frequencies such as radio frequencies.

It is necessary for you to have knowledge of the foregoing so that you may have an idea of how inductance acts upon such circuits to better enable you to bring about a line of reasoning which will help you when we arrive at the point where high frequency is used in a radio circuit. This same basic idea is to hold in the explanation of capacity in an alternating circuit of high frequency when we will have progressed to that part of the work.

SELF INDUCTANCE

Self inductance is the phenomenon of an electric circuit which causes the generation of a second electromotive force in the circuit whenever the current is increasing, decreasing, or varying in its rate of flow.

The applied electromotive force, which we will call the first E.M.F., is responsible for the flow of current in the circuit, but the current while it is in any way varying, either increasing or decreasing, starting, or stopping, is causing a second electromotive force to appear in the same circuit.

If we have a long straight wire forming a circuit of 22 ohms resistance in which 5 amperes are flowing, at an electromotive force of 110 volts, we will find that, upon closing the circuit by means of a switch, the ammeter will almost immediately register 5 amperes and, upon opening the switch, a small spark will appear at the switch points.

Winding the same conductor about an iron core as shown in Figure 1 and again closing the switch "S" the ammeter will again register 5

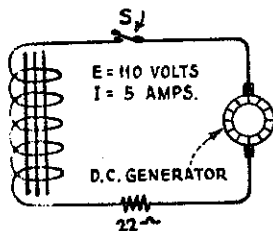


Figure 1

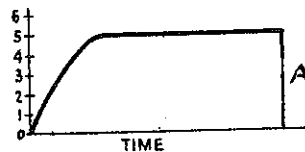


Figure 2

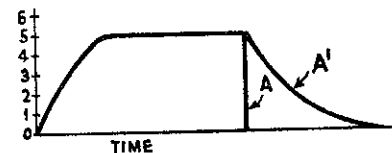


Figure 3

amperes as the resistance of the conductor has not been changed. It will be noticed, however, if it was possible to observe the rise of the needle, that it requires a considerably longer time for the needle to indicate the full value of 5 amperes in the second circuit arrangement, than it did in the first. Upon opening the switch "S" this time a much larger spark will be seen to occur at the switch contacts, which fact is evidence that the current still tends to flow in the circuit.

It should be noted that this spark is larger than that produced when the circuit was in the first arrangement of a straight conductor; this is evidence that the circuit now has greater inductance.

That which takes place is as follows: When a circuit as shown in Figure 1 is closed, current at once starts to flow through the coil and increases in value until the maximum current value is reached.

It does not rise to its full value instantly but does so gradually, as shown by the sloping part of the curve in Figure 2. The reason for its gradual rise instead of an instantaneous rise is due to the expanding magnetic field which always is in a state of change whenever the current varies. The instant the current starts, this magnetic field springs into being and expands, cutting the conductor and inducing in this same conductor a secondary electromotive force, called the self-induced or counter E.M.F., which tends to prevent the increase in the current producing it.

It is this self-induced E.M.F. which, by its opposition to any change in the flow of current, retards the rise of current in the circuit. The greater the self-inductance of a circuit the more pronounced will be this opposition to any change whatsoever in the current. In a circuit, such as that of Figure 1, in which the coil sets up a strong magnetic field and hence has a high value of self-inductance, whenever an attempt is made to quickly increase, reduce, or stop the current flow, the resulting self-induced E.M.F. exerts a marked opposition to such a change. It will always oppose an increase in current and, when the current is decreased or stopped, will also oppose such a decrease by attempting to maintain the current at its original maximum value.

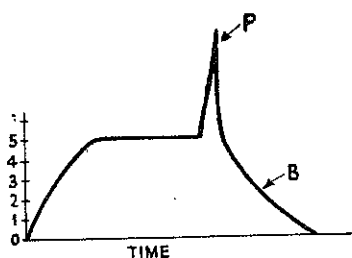


Figure 4

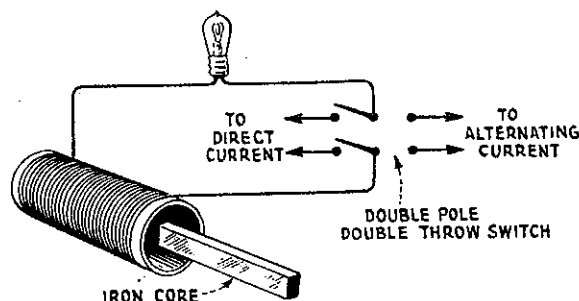


Figure 5

The applied electromotive force, which caused the current to flow during the time the current was increasing, was being opposed by the self-induced electromotive force, and it is the difference between these two voltages which determines the momentary current value. When the current is increasing at its greatest rate the self induced voltage attains its greatest opposing force, but when the current reaches its maximum value and becomes steady i.e., having no variation, this self induced E.M.F. then disappears. Although the counter E.M.F. becomes nil when the current has reached a maximum steady value, energy, however, is still present in the form of an electromagnetic field.

If a circuit possesses a very low self-inductance, upon opening the switch "S", the current will not drop instantly to zero, as shown by the abrupt cut off line A, in Figure 2, but will gradually decrease as shown by the line A', in Figure 3. If, on the other hand, the circuit possesses relatively high inductance then, upon opening the circuit and thus suddenly stopping the source of current, there will

be a momentary heavy surge of current in the circuit after which the current dies out as shown in Figure 4.

It must be remembered that, during the gradual rise of current in the circuit, energy was also being gradually stored up in the medium surrounding the coil in the form of an electromagnetic field. Since this magnetic field is dependent for its existence upon a flow of current through the coil, the instant the switch "S" is opened, thus stopping the flow of current, the field immediately collapses upon the coil. This collapse of the field upon the coil induces therein a voltage and current which flows in the same direction as the original current. This constitutes opposition to the inevitable decrease of current by tending to maintain the current flow at its original maximum value. In other words, the flow of current through the coil has resulted in some of the current being used to create an electromagnetic field. When this current ceases the field collapses and the energy stored in this field is returned to the circuit in the form of electrical current. As already explained, this inter-play of forces in the circuit is such that the self-induced voltage and current always opposes any change. It is the sudden falling of this magnetic force about the conductor which causes the momentary heavy surge as shown in Figure 4 by the peak curve marked P.

What have we discovered by the foregoing? Summing up these causes and effects we find the following:

- (1) When an E.M.F. is applied to a circuit current starts to flow and a magnetic field springs up.
- (2) As the current increases the field increases, cutting the conductor and thereby creating a counter E.M.F. which tends to prevent the current from further increase and which is called the SELF-INDUCTION of the circuit.
- (3) Self-induction in this particular instance constitutes an opposing force to the original current.
- (4) Time is required for the original current to overcome the opposition offered by the self-induction of the circuit.
- (5) When the current reaching its maximum value and remaining steady, the field ceases to cut the conductor and self-induction ceases.
- (6) On disconnecting the source of applied E.M.F. the original current ceases to flow, thus allowing the magnetic field to collapse, which again cuts the conductor thereby inducing an E.M.F. and creating a current which flows in such a direction as tends to maintain the current flow in the circuit.
- (7) The self-induction of an electric circuit always opposes any change of current taking place.
- (8) In a direct current circuit the effect of self-induction is apparent only for a moment while the current is changing in value, either increasing or decreasing, or only at the time the circuit is opened and closed.

Electromagnetic Inertia is a term sometimes used to better express self-inductance for it acts quite similar to the inertia which is found in the study of mechanics. For example, a fly wheel tends to remain at rest and, when force is applied in a manner which will cause the wheel to revolve, it will require time plus the force to cause the wheel to revolve at a given speed. When it is desired to stop the revolving wheel force is again applied and time is required to bring the wheel to a dead stop.

The energy which is stored in the revolving mass must be absorbed as it is gradually brought to its original state of rest. Inertia will oppose any increase or decrease in the existing speed of a moving mass. The same principle is involved in the case of electric current flowing through a coil where self-induction (electro-magnetic inertia) opposes any increase or decrease in the flow of current.

The current value in an alternating current circuit is continually changing in value, consequently the magnetic field is continually changing,- building up one instant and collapsing the next, opposing the rising current and tending to maintain the flow of the decreasing current. An experiment which serves to visibly indicate the effect of the inductance of a coil both with and without an iron core when, first, direct current is flowing through the coil and, second, alternating current, is explained in the following paragraphs.

Employing one of the coils we used in our study of electro-magnetism, we will connect a lamp in the circuit instead of the meter and change the source of supply by the use of a double-pole, double-throw switch, allowing us, by throwing the switch, to send either alternating or direct current through the coil. In Figure 5 the voltage of both sources is 110 volts.

First throw the switch to the left, thus connecting the direct current with the coil. The lamp lights brilliantly at once. With the lamp burning move the iron core in and out of the center of the coil. It will be noticed that there is no change whatever in the brilliancy of the lamp; it burns just as brightly with the iron core in the center of the coil as it does with it out.

Now withdraw the iron and throw the switch to the right, thus connecting the coil to the alternating current source. At once there is a difference in the brilliancy of the light of the lamp. It is burning dimly. Thrust the iron core in the center of the coil as you did before and note that the lamp becomes very dull. Removing the iron will produce a change in the brightness of the lamp but, in either case, with the iron in or out of the coil, it does not burn as brilliantly as it did when connected to the direct current source of supply. In this experiment the circuit has not been changed in any respect; the actual (ohmic) resistance has remained the same in both cases, and the voltage maintained at the same pressure.

When direct current was employed the lamp was not effected but burned with the same brilliancy with and without an iron core.

On connecting the same pressure of alternating E.M.F. to the circuit there was a difference in the burning of the lamp, and since no change was made in the ohmic resistance of the circuit it is obvious that there must be some other pronounced effect in the circuit when A.C. is employed and that this effect reduced the amount of current flowing in the circuit as evidenced by the dimming of the light.

Since alternating current is continually changing in value the field also changes and tends to keep up a continual counter E.M.F. opposing any change in the applied current; when the iron core was inserted a greater effect was noticed by a further dimming of the lamp due to a greater field concentration which was produced by the iron core because the core furnishes a much better magnetic path for the magnetic field than air. It is evident from this experiment that the counter E.M.F. of self-induction of the coil when alternating current is used, tends to reduce, or oppose, the flow of the current producing it. It is also evident that the effect of inductance will oppose the current to a greater extent than would be the case if straight resistance were employed, - independent, of course, upon the frequency of the current and the respective values of inductance and resistance.

From this we may say; - "The electromotive force of self-induction opposes at all times any change in the current producing it, and its value is proportional to the rate at which the producing current varies." For example, if we cause the current to alternate more rapidly, the greater will be this opposing force. In a direct current circuit the opposition to the flow of current is caused by the ohmic resistance in the circuit and represents a loss of energy because the energy is dissipated as heat, while in an alternating current circuit this opposing effect is caused by the counter E.M.F., or self-induction, which simply reduces the current and all that is required is a greater applied E.M.F. to force the same equivalent current through the circuit. Therefore the losses are not as great in an A.C. circuit employing inductance as in a circuit using resistance.

REACTANCE

We have seen how a conductor wound in the shape of a coil or helix will, when placed in an A.C. circuit, limit the current flowing through the circuit as was proven in the experiment with the circuit of Figure 5.

The counter E.M.F., or self-induction, of the coil was the cause of this retarding phenomena and is called the Reactance. When only inductance is involved this opposition is called Inductive Reactance and is shown in abbreviated form as X_L (read as X sub L), and is expressed as so many ohms reactance.

Reactance caused by the presence of capacity (condenser) in the circuit is called the Capacitive reactance X_C (read as X sub C), and which is covered in detail in your next lesson.

Inductance in an A.C. circuit will cause the current to lag behind the voltage. This is caused by the induced E.M.F. which is always present whenever there is a change in the current flowing in the circuit; the induced E.M.F. will always oppose any change in the current.

In any alternating current circuit the current is always changing and, when inductance is present in this circuit, there will always be an induced E.M.F. opposing these changes in the current. As the current is rising in value the induced E.M.F. opposes this rise and the momentary values of the induced E.M.F. and the applied E.M.F. Therefore, the increase of current takes place later than the rise of the applied E.M.F. and since this is the case the current is therefore said to lag the voltage.

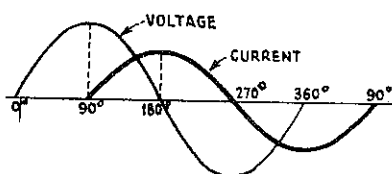


Figure 6

When the applied E.M.F. is decreasing and the current is decreasing the induced E.M.F. again opposes the decrease of the current and tends to keep the current at a larger value than would occur from the decreasing applied E.M.F. alone. This effect of the induced E.M.F., which tends now to uphold the current values, causes

the current to again lag the applied E.M.F. Thus throughout the entire cycle the current lags behind the applied voltage, and when the circuit contains inductance only, and by that is meant negligible resistance or capacity, the current will be reaching its maximum and minimum values 90 degrees behind the maximum and minimum values of the applied E.M.F. or, more specifically, the current lags the voltage by 90 degrees. Figure 6 shows this condition in curve form.

The inductive reactance of any circuit is equal to 6.28 times its inductance in henries, times the frequency of the current, and is really another or additional resistance added to the circuit besides that of actual ohmic resistance, and it is measured in ohms. Thus we speak of a circuit as having so many ohms reactance but, as we have already stated, reactance does not always constitute a loss in the circuit as resistance does; it merely calls for a higher E.M.F. to be applied to force a given current through the circuit than if resistance only were present in the circuit.

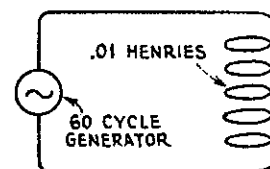


Figure 7

Inductive reactance is determined by the following formula:

$$\begin{aligned} \text{Inductive reactance } (X_L) &= 2\pi f L, \text{ or } 6.28 \times f \times L \\ f &= \text{frequency in cycles} \\ L &= \text{inductance in henries} \\ 6.28 &= (2 \times 3.1416) \text{ usually written } 2\pi. \end{aligned}$$

Supposing the coil in Figure 7 has an inductance of .01 henries and the alternator is supplying E.M.F. at 60 cycles. What would be the reactance in ohms in this circuit? From our formula:

$$X_L = 6.28 \times f \times L$$

$$X_L = 6.28 \times 60 \times .01 = 3.7680 \text{ ohms reactance.}$$

CHOKE COILS

In alternating current circuits inductance coils having certain values may be used as choke coils to limit the current flow, the name "choke coil" being used because of the choking or retarding effect upon alternating current by the self-inductance of the coil. This principle is used to regulate the flow of current in alternating current circuits because of the economy attained over the use of resistance which absorbs the energy and gives it off as heat.

FORMS OF INDUCTANCE

Inductance in radio takes various forms. The antenna itself constitutes a form of inductance, referred to as distributed inductance due to the magnetic field which is set up about the antenna wires. You are perhaps familiar with this form of inductance as shown in Figure 8.

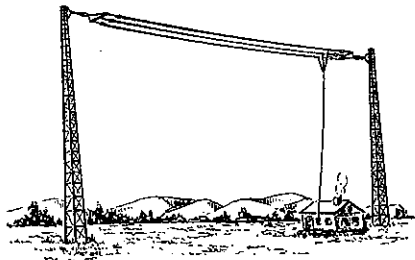


Figure 8

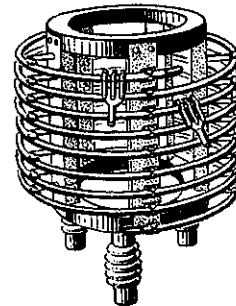


Figure 9

Connected to the antenna lead-in is another form of inductance called lumped or concentrated inductance which, in the transmitting set, appears sometimes as a helix of heavy copper tubing or solid wire. This type of inductance is shown in Figure 9.

Figures 10 and 11 show types of inductance coils commonly used in receiving sets.

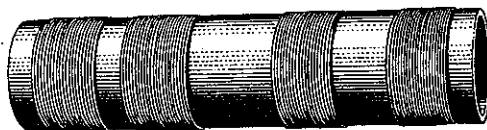


Figure 10

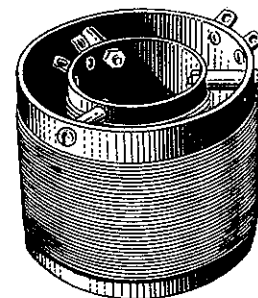


Figure 11

The next part of our work will have to do with capacity. Capacity and inductance together in an electrical circuit produce interesting

results and a well founded knowledge of both is needed to enable you to thoroughly understand radio circuits.

NOTE. The constant 6.28, used in a formula in this lesson, is found by multiplying 3.1416 by 2. Many students become confused when they see the symbol π . The exact mathematical relation this holds to subjects of electricity is complicated and will not be discussed here, however, it might be well to outline generally its use thus dispelling the doubt many students have in regards to it. π (pi) is the sixteenth letter of the Greek alphabet and is pronounced "pie"; it has been adopted by mathematicians to show the relation existing between the diameter and circumference of a circle. Numerically it is equal to 3.1416 and it is used to denote that the circumference of a circle is equal to 3.1416 times its diameter.

Electrical engineers have adopted the symbol π to denote magnetic force and, omitting the mathematics involved, we will explain it as follows: At a certain distance from a certain magnetic pole the magnetic field has a certain strength, it being considered that there is one line of magnetic force for each square centimeter. As this magnetic force from a magnetic pole is equal in all directions from the pole and since the surface of a sphere has a radius equal to unity, the magnetic lines of force from this certain magnetic pole will be equal to $4 \times \pi$. In other words, the magnetic force resulting from a current flowing through a coil is equal to $4\pi \div 10 \times$ the product of amperes $\times$ the turns of wire in the coil, or m.m.f. = $I \times$ turns.

EXAMINATION - LESSON 14

1. Does self-induction exist in Direct Current circuits?
2. Does induction take place when the magnetic field is steady?
3. (a) How would you describe the effect of inductance in a Direct Current circuit? (b) In an A.C. circuit?
4. Write briefly what you know about inductive reactance.
5. What are choke coils and why are they used?
6. What effect is apparent when iron is introduced as the core of an inductance coil?
7. What is the unit of inductance?
8. Does an increase in current in a conductor increase the magnetic force about that conductor?
9. What is the product of 2π ?
10. Where is the following formula employed: $X_L = 2\pi fL$? Give an example of its use.